Preprint
UCRL-JC- 152692

ITER Model Coil Tests Overview: Nb3Sn strand properties in cable-in-conduit-conductors

N. N. Martovetsky

This article is submitted to International Cryogenic Materials Topical Conference in Enschede, Netherlands, May 25-28, 2003

April 14, 2003

U.S. Department of Energy

Lawrence Livermore National Laboratory

PACS: 74.60.Jg Critical currents
74.62.-c Transition temperature variations

Abstract.

During the ITER Model Coil Program two large coils and three Insert coils were built and tested. The test campaigns provided very valuable data on the Conductor in Conduit Cable (CICC) properties. The tests showed that the Nb3Sn strands in CICC behave differently than so-called witness strands, which underwent the same heat treatment. The paper describes Volt-temperature characteristics (VTC) and Volt-Ampere characteristics (VAC) measured in the tests, presents comparisons with the witness strands, and interprets the test results.

Key words: Niobium-tin, Cable-in Conduit, Critical current, N-value

Introduction

It is well known that the intermetallic Nb3Sn is brittle and strain sensitive. The magnets that underwent react and wind fabrication frequently showed a significant degradation. The most notable examples of react and wind technology were the large coils of the T-15 [1] superconducting tokamak and a Westinghouse coil for the LCT project [2]. During the T-15 R&D and model coil program, it was noticed that the strands assembled in the conductor and bent on different radii show not only a degradation in the critical current (Ic) but also a significant increase in the broadness of the superconducting transition; in other words, a reduction of the N-value. The N-value is the exponent in the electrical field approximation in a superconductor: $E = E_c (I / I_c)^N$. While the critical current dropped by a factor of 30-45%, the I_0 parameter went down by a factor of three, which corresponds to a 6× decrease in the N-value. Here I_0 is the parameter in the following approximation of the VAC: $E = E_c \exp[(I - I_c)/I_o]$. Within 2-3 orders of magnitude of voltage, this relationship is indistinguishable from the one above. Near Ec the relationship between the N-value and Io is N≈Ic/Io. It was noticed that the change of broadness of the transition to the normal state was more apparent than the change of critical current. Also, the critical current decrease from bending was significantly more than it was expected from uniaxial tension to the same peak strain. By that time it was known that decrease of the N-value might be caused by increased inhomogeneity of the filaments due to partial breakage of filaments. Why bending caused more severe damage than the uniaxial tensile strain is still not understood. Long ago we learned that the increase of the broadness of the transition to the normal state in the Nb3Sn conductor is a reliable indication of the degradation in the conductor.

Similarly, the Westinghouse LCT coil [2] showed a very broad transition to normal state and a significant critical current degradation. Therefore, it was decided to develop a wind–react-transfer technique, and successful coils were built by the MIT group that demonstrated a feasible technology for large fusion magnets with low or no degradation. It was a big step towards full realization of the superconducting strands potential in the CICC, but transformations of the N-value in CICC were not studied consistently then. The ITER conductors are significantly larger than their predecessors and one of the goals of the Model Coil program was to study behavior of such conductors in the ITER relevant conditions, including transitions into the normal state to see if there is any change between the isolated strand and the strand in the CICC.

ITER Model Coil expectations before tests

In the ITER EDA and Model Coil programs, it was expected that the strands would realize their properties in the CICC in accordance with their strain conditions, but a 2 K safety margin was accepted to ensure success. Low CTE (coefficient of thermal expansion) conduits, like Incoloy 908 or titanium, were expected to fully realize the strand properties in CICC as measured on a strand with no applied stress. The stainless steel conduits were expected to have reduce properties compared to a strand measured on the standard titanium barrel, but better than due to the CTE mismatch between the steel and Nb3Sn strand due to imperfect bond between the conduit and the cable. The subscale experiments carried out at the FENIX facility at LLNL [4], the SULTAN facility at CRPP [5,6] and some subscale experiments [7] suggested that the CICC in the stainless steel experiences significantly less [4,5] degradation than would have been anticipated from about 0.7% mismatch in shrinkage between stainless steel and Nb3Sn strand from the reaction temperature down to the operating temperature. Data from three samples tested at the FENIX facility projected that the effect of the mismatch will be at the level of –0.55% due to some slippage of the cable inside the conduit [4]. Expectations for the TFMC were set at CTE degradation equivalent to –0.61%.

A full scale conductor in an Incoloy jacket tested in the SULTAN facility [8] showed a 15% degradation in Ic at the peak field, or even less at some runs [10] although error bar was not very narrow. Practically all short full size conductors showed the effect of nonuniform current distribution originating from the joints. Therefore, the fact that the quench currents in the samples exceeded expectations from the strand Ic at peak field suggested that the achievable currents in the Model Coils should be even higher than in the short samples since the current redistribution is much better in long coils.

<u>CS Insert Test results.</u> Figure 1 shows VTC of the CS Insert in comparison with the strand witnesses, which showed 162-164 A at 12T, 4.2 K. The measured N-value in the CS Insert was 8.4 compared to the N=21 in the strand at the same current. After cycles and quenches, the Tcs decreased by almost another 0.5 K, making the total loss of temperature margin about 1.5 K compared the strand-witness. In terms of the critical current loss, this is equivalent to almost 40% degradation at 12 T and 4.2 K. The N-value in the cable was much lower than in the strand but then did not change much as Tcs continue to decrease due to cycles and / or quenches.

Figure 2 represents the evolution of the Tcs and N-value in the CS Insert during the first test campaign in 2000. As one can see, an apparent change in the Tcs due to cycles / quenches does not correspond to the N-value change.

Figure 1 also shows effect of the current distribution at electrical fields below 3-4 μV / m, where VTC is strongly distorted. Above this level the current is distributed uniformly because longitudinal voltage is an order of magnitude larger than that across the joints, thus imposing significant equalizing resistance in all strands. The recent ITER joint studies did not reveal a strong imbalance between the strand resistances to the terminal [8], thus nonuniform distribution is very unlikely above a certain voltage, about at 3-4 μV / m judging by Fig. 1. This leads to conclusion that measurements of the VAC or VTC of the CICC represent an average strand in the CICC with its critical current and N-value, not an interaction between strands with high N and Ic. Uniform current distribution is not always possible to fulfill in short sample measurements due to the short length and smaller overall voltage across terminals. However sometimes Ic expected was close to the measured [5,6], even in short sample tests, which suggests that the effect of nonuniform current distribution is suppressed at voltages of about 100 μV or higher. In long coils the total voltage reaches 1000μV or higher before quench, which makes non-uniform distribution very unlikely.

<u>CSMC layer 1A.</u> Measurements of the CSMC were conducted during three test campaigns in 2000-2002. After all campaigns, the CSMC layer 1 showed degradation of about 0.5 K against the witness strand data. In terms of Ic loss, it was about 20-25% in comparison with the witness strand at the resulting strain of 0.16% at 40 A per strand in 13 T. The degradation is slightly higher if compared against production strand properties rather than strand-witness [9]. The degradation seems to be less pronounced or vanishing at lower currents, which leads to hypothesis that the electromagnetic loading is responsible for this effect [10]. The N-value for CSMC conductor 1A was significantly lower than measured in the strand. At 40 A per strand, the measured N-value in the CSMC was 6-7 while the original strand N-value was about 16-20 [11].

<u>TF Insert.</u> The TF insert, which used titanium conduit and stainless steel structure, also showed significant Ic degradation and a reduction in the N-value. The tests showed that the properties of the conductor along the length do not vary much. The Ic degradation in the CICC was about 35% at 12 T, 10 μV / m and 46 kA or 1.45 K in terms of the lost temperature margin [12]. Similar to the CS Insert and CSMC the N-value was significantly lower than in the strand [13], see Fig.3.

<u>TFMC.</u> The TFMC showed somewhat lower performance than corresponded to expected equivalent strain of –0.6-0.7% by about 20% in terms of Ic or about 0.4-0.5K lower temperature margin [14]. Expressed in terms of the strain, it is equivalent to 0.15-0.2% additional compressive strain. This relative change versus expectations is less than in the TF and CS Insert, since a large degradation was expected already due to the stainless steel conduit. Overall degradation in the TFMC is higher than in the low CTE conduits, as expected. The N-factor in TFMC also dropped from 22-25 [11] to 7-10 [14] at 111 A per strand.

NbAl insert. Although the NbAl Insert is not directly related to the Nb3Sn strand in question, testing the NbAl Insert was very educational for interpretation of the Nb3Sn CICC results. The NbAl has much smaller strain sensitivity than the Nb3Sn [15]. There was no degradation or noticeable change in N-value. The NbAl Insert showed CICC can realize full capacity of the strands critical currents if not overstressed. That suggests that the degradation in Nb3Sn has mechanical origins, possibly coming from fabrication and / or electromagnetic loading. Also, the fact that the N-factor in the cable was the same as in individual strands means the Inserts have sufficiently high voltage and low interstrand resistance to allow efficient current redistribution. This suggests there is a uniform current distribution and what we measured on the CICC represents the average strand behavior in the cable, not interstrand current transfer.

Summary on the ITER Model Coil DC results

Figure 4 shows a summary of the CICC performance versus strand–witnesses recalculated for 12 T. It is clear that the TFMC has the largest loss of the current carrying capacity of the strands, mostly due to thermal expansion mismatch between the stainless steel conduit and the Nb3Sn cable. The TFMC showed just above 50% of the potential current carrying capacity of the original strands. The CS Insert and the TF Insert have lower percentage loss; the CICC had about 65% of the witness strand capacity, but this loss was not expected. The CSMC has the lowest loss of current carrying capacity between other ITER coils– 20-25% below the Ic of the witness strands.

Figure 5 shows measurements of the N-value in the Nb3Sn and NbAl CICC, including subscale sample tests at CRPP [16]. The NbAl CICC N-value changed very little from the original strand N-value, while Nb3Sn CICC N-value dropped significantly by a factor of 2 to 3. This indicates that the N-value is more sensitive parameter than Ic or Tcs for detecting CICC degradation.

The ITER Model Coil Program showed that the industry is ready to build the ITER magnets to meet the requirements if a proper safety margin is chosen. On the other hand, the degradation was worse than expected. From comparison with strain-insensitive Nb3Al CICC, it is clear that the degradation in the Nb3Sn CICC is associated with strain. The Ic and the N-value both decrease when degradation is observed, but the N-value drop is much more pronounced. All Model Coils show significant degradation and N-value reduction in comparison with the strands. All coils were very stable. The coils unique features include different sensitivity to cycles / quenches. For the CS Insert, Tcs was reduced by about 0.5 K after 2000 cycles and some quenches; the CSMC had reduction by 0.1-0.15 K. The TF Insert degradation was less than 50-70 mK; the TFMC did not have noticeable degradation. Similar conductors (CSMC and CS Insert) operating in similar conditions showed different degradation, which may imply that higher performance strands may experience higher degradation.

CICC in the SS conduit is expected to degrade by about 45-50% in comparison with the strand on the standard barrel at 12 T, while a CICC with low CTE conduit may lose 20-35% of it’s current carrying capacity at 5 K, 12T. In terms of the temperature margin, the loss at 60 A per strand it is about 2.2 K for TFMC-like strand (about 1.7-1.8 K was anticipated due to conduit compression) and about 1.5 K loss for the CS and the TF Inserts. No performance loss was anticipated before the program for low CTE conduits.

Mechanisms of degradation and future R&D

There are several speculations under discussion about exactly what is causing degradation and the N-value change in the Nb3Sn CICC. It is unlikely that all of the degradation is caused by a uniaxial contraction by the conduit, since the total amount of contraction is not sufficient to cause that. The strand data indicate [3,10] that the change in strain from –0.2 to even –0.7% is not sufficient to explain observed reduction of the N-value.

A CICC model proposed in [10], assumes that the strands in the cable experience severe bending since they are supported only at the cross over points, which causes changes of critical currents in the filaments and substantial current transfer. That reduces N-value and Ic. This hypothesis is being tested in experiments that will try to reproduce the Ic and N-drop similar to the observed changes on the ITER CICC as a result of bending. Another hypothesis assumes [17] that cracking of the filaments is taking place only in the stretched areas, which causes drops in Ic and N due to intensive current redistribution. Pre-compression by a conduit reduces or eliminates amount of filament that will see tension due to bending under BxI load, which explains the smaller than unexpected degradation in TFMC. Yet another hypothesis is the pinching of the strands by electromagnetic forces. It was reported in [18] that the strands show clear indentations at the cross over points. Since Nb3Sn is known to have high sensitivity to the transverse loads, the plastic deformation of the strands gives a strong indication that it may have caused some damage. It is shown in [19] that strands extracted from the cable have significantly reduced N-values and Ic without bending. These hypotheses require more tests to verify this mechanism.

Conclusion

All ITER Model Coils achieved their operating points with no training, but showed some degradation. The coils were designed with a temperature margin of 2 K at the operating current, but degradation took a significant part off that margin. In all cases, the N-value in the CICC was significantly lower than in the original strands. It appears that the N-value in the CICC reflected actual transformations taking place in the strands, not inter-strand current transfer effects. Comparison with low strain sensitive NbAl CICC points to mechanical reasons for degradation. The community proposed several mechanisms of degradation, and the R&D in the near future should help to understand the mechanism of degradation and possibly develop ways to mitigate it.

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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Figure captions:

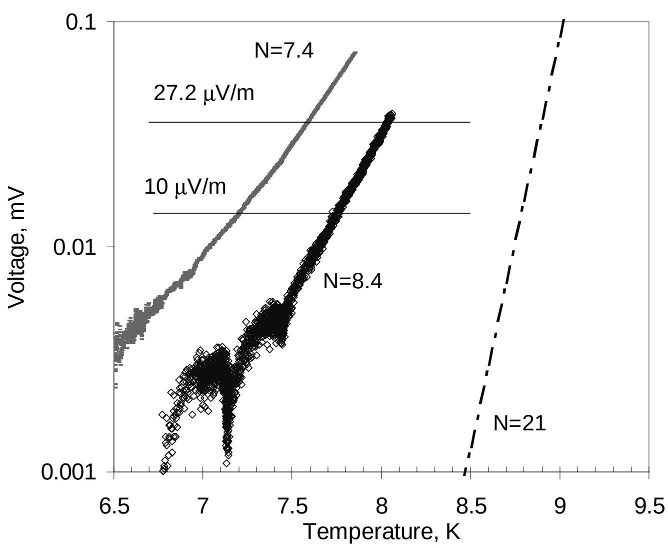
Fig. 1. Volt-Temperature Characteristics (VTC) of the CSI before and after cycles (lower Tcs) and anticipated VTC from the witness strand data at 13.1 T at 40 kA.

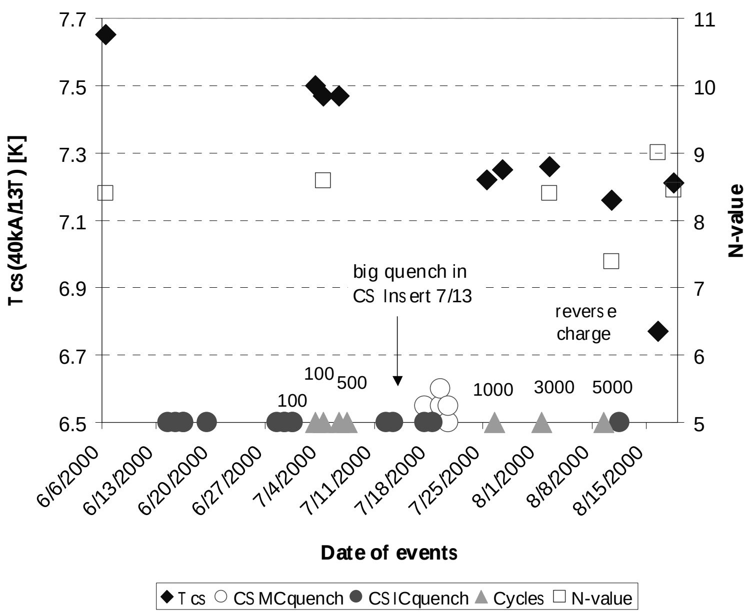
Fig. 2. Tcs and N-value change in the CS Insert during the test campaign

Fig. 3. N-value versus Ic correlation between the TF Insert strand and the TF Insert CICC

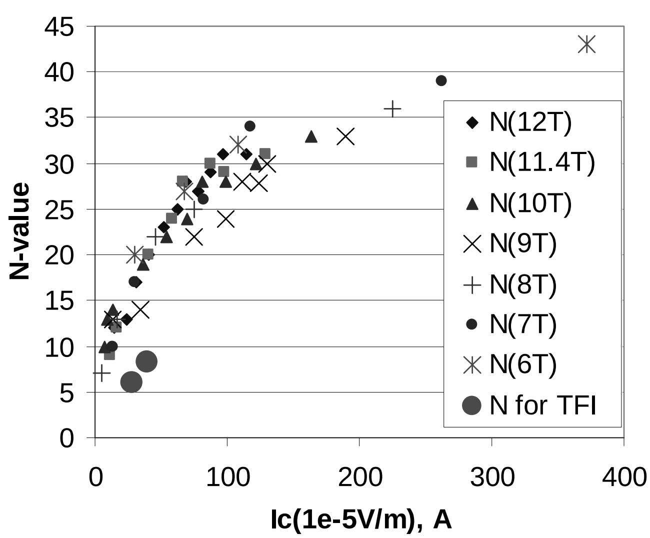
Fig. 4. Summary of the ITER Model Coil CICC performance versus witness strand at 12 T and 10 μV / m.

Fig. 5. N-value of Nb3Sn CICC vs Nb3Al CICC. See text for explanations.

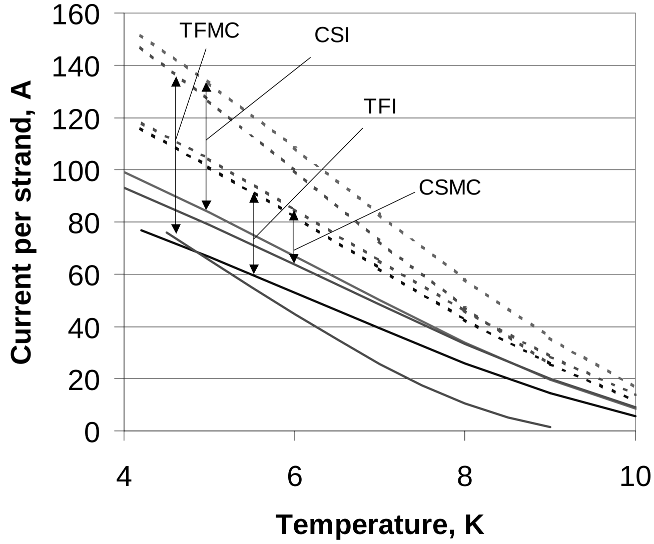




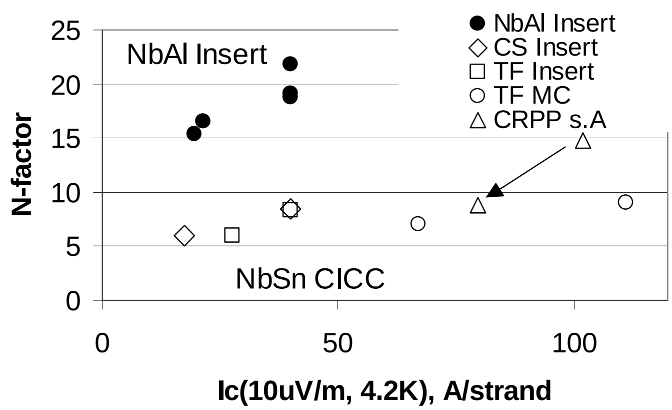
Tcs (40kA/13T) [K]
N-value
Date of events
big quench in CS Insert 7/13
reverse charge
100
100
500
1000
3000
5000
Tcs
CS MCquench
CS ICquench
Cycles
N-value



N-value
Ic(1e-5V/m), A
N(12T)
N(11.4T)
N(10T)
N(9T)
N(8T)
N(7T)
N(6T)
N for TFI



Current per strand, A
Temperature, K
TFMC
CSI
TFI
CSMC
160
140
120
100
80
60
40
20
0
4
6
8
10



N-factor
Ic(10uV/m, 4.2K), A/strand
NbAl Insert
NbSn CICC
NbAl Insert
CS Insert
TF Insert
TF MC
CRPP s.A
25
20
15
10
5
0
0
50
100

University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551